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Modelling Zero Energy Buildings: parametric study for the technical optimization

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Abstract

This study was born in the context of new challenges imposed by the recast of the EU Energy Performance of Buildings Directive. The aim of this work is to develop strategies to identify and investigate the relationship between decisional variables within a nZEB design concept, providing a useful method to deal with a huge number of simulations corresponding to a large number of building configurations in order to find one optimized constructive solution. The method combines the use of the TRNSYS® with GenOpt®, in an iterative input-output process.
The case study is an existing low-consumption single-family house located in Amberieu-en-Bugey, Rhône-Alpes, France. After a description of the case-study and of its TRNSYS model, the definition and the settings of the parameters are illustrated and a parametric study is performed in order to evaluate the impact of the variation of various envelope features on the annual energy consumptions. The resulted optimal design solution reduces by 20% the current annual energy performance, validating the used optimization method and providing general principles for a good nZEB design.

Selection and peer-review under responsibility of KES International

Keywords: design concept; design parameters; decisional variables; building simulation; optimization; nZEB

1. Introduction

In the context of the European Union efforts to reduce the growing energy consumption, it is widely recognized that the building sector has an important role, accounting 40% of the total energy consumption in the European

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Union [1]. The recast of the Directive on the Energy Performance of Building (EPBD)[2] imposes the adoption of measures to improve energy efficiency in buildings in order that all new buildings will be nearly Zero Energy Building (nZEB) by 2020. This practice could lead to greenhouse gas emission reduction in the building sector. As the results in term of energy efficiency are evaluated at a global (or at least European) scale, it is remarkable that a good nZEB design is strictly related to the local scale, depending on climatic data, available technologies and materials, population lifestyle.

The architectural design process (be it: new construction, renovation or retrofit) includes important choices that may heavily affect the energy performance of the building, mostly related to the envelope design. Sometimes, for a given plan and volume, a small variation in the envelope construction may produce a significant variation in energy needs. The challenge is to quantify these variations and offer to designers further help in decision making in the context of the constraints of design environment.

1.1. Scope of the work

Scope of the work is to develop a method able to quantify the relationship between some of the decisional variables of the ZEBs design, the related parameters and their range of variability. This is done by means of a parametric study, aiming at identifying:

- The impact of each parameter on the total annual energy consumptions;
- The optimal design solutions from the energy point of view.

2. Materials and methods

2.1. The case study

The Case-Study Building (CSB) is a new single-family house located in Amberieu-en-Bugey, Rhône-Alpes, France. It could be considered as representative of new construction of single-family house in this French region [2]. Some pictures are shown in Fig.1.

The net floor area of the conditioned volume is equal to 155 m^2. Coherently with principles of passive/low consumption houses, in order to reduce heat loss due to windows and benefit of solar gains, the maximum of large openings are south-oriented (49% of Total Glass Surface -TGS- on the south external wall, 19% on the south roof slope) while the percentage of openings in east and west orientation is less relevant (respectively 10% and 15% of TGS) and there are only very small north oriented openings (7% of TGS). Window area is approximately 1/5 of the floor area: the minimum imposed by the national regulation [3], which is equal to 1/6 of the floor area, is largely exceeded. A roof overhang protects south-oriented windows. The heated volume has a compact shape that minimizes the exchange surface between the outside and inside. S/V ratio is equal to 0.68 m^{-1}.

Walls are made of concrete blocks, while the roof has a wood structure. Thermal insulation is made on the internal side, thereby creating a thermal bridge on the intermediate floor, which has been limited by use of thermal bridge breakers. However, this solution eliminates thermal bridges at the slab and roof levels. At the moment, 20 cm of insulating material are used on external walls, 30 cm on the slab and 40 cm on the roof. Moreover, a double-height internal wall made of stones and concrete increases the inertial mass.

A blower door test was performed, attesting the air tightness of the house equal to 0.6 m^3/hm^2.

The house is also equipped for monitoring: 20 thermo-hygrometer sensors register the internal air temperature, 4 sensors capture the internal temperature of the inertia wall and a weather station reports weather data. As the house is uninhabited, the occupancy is simulated by a home automation system that is able to switch on/off the lights and appliances and the human simulation devices depending on user-defined scenarios.

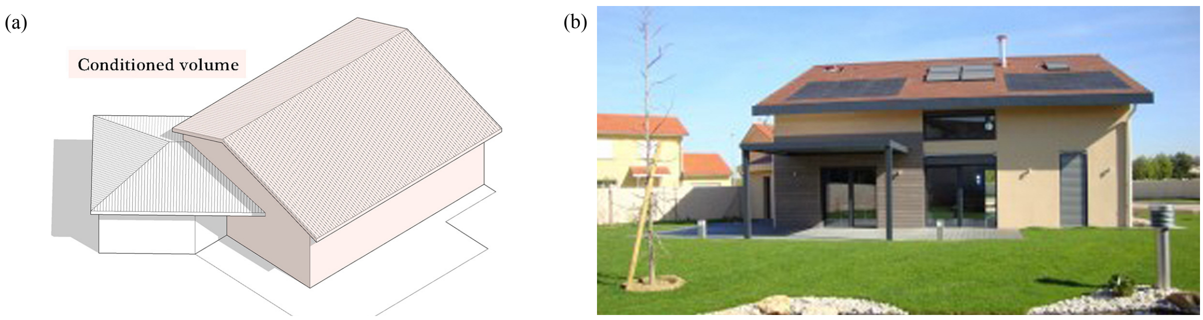

Fig. 1. Representation of CSB. (a) Conditioned volume. (b) Picture of the south front.

2.2. Dynamic building simulation: model and calibration

CSB was modeled using TRNSYS® [4], dynamic building simulation program. As shown in Fig. 2, each room was modeled as a thermal zone, in order to better evaluate the evolution of temperature and the thermal exchange from one zone to the other, as the HVAC system is considered active only in the main rooms of the house. Set-point temperature for heating (19°C) and cooling (26°C) was set only in the living-room (PP), in the bedrooms (C1, C2, C3) and in the mezzanine (M), while other zones as restrooms (R1, R2), dressing (D), laundry (B) and passages (DGT1, DGT2) are supposed to take heat (or cool) from transmission through internal walls and doors. The garage (G) is considered a non-conditioned zone.

The standard meteonorm weather file of Amberieu-74820 was used in the simulation. Lighting and appliance loads (8 W/m^2, dressing and passages excluded) and occupancy (100 W/person) were modeled using schedules for a standard 5 people family working life, week-ends are taken in account but holidays are not considered. The sum of infiltration and ventilation rate is fixed equal to 0.7 ach in all the zones.

The results of the model, in terms of indoor temperatures and energy consumptions, were compared to the real data obtained from the monitoring system. The model was then calibrated in order to avoid differences in results bigger than 15%.

Since the aim of this paper is to evaluate energy needs depending on the building envelope features, the energy system was not taken into account for building model and simulation. The TRNSYS® calculation of sensible heating and cooling demands for all zones (SQHEAT-NTYPE 32 and SQCOOL-NTYPE 33, outputs of Type 56-Multi-Zone building) was considered. Based on these settings, heating needs of the CSB are equal to 48 kWh/m^2/year, while cooling needs are estimated to be 12 kWh/m^2/year.

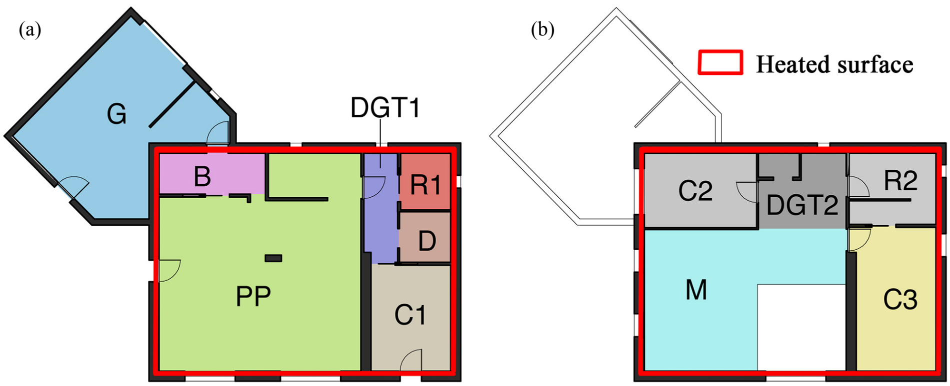

Fig. 2. Plans of the CSB with defined thermal zones. (a) Ground floor. (b) Second floor.

2.3. Parametric study

As already mentioned, a parametric study on the CSB was done with the purpose of estimating the impact of the variation of different features of the building envelope and geometry on the heating, cooling and total annual energy needs. In order to ensure the easy and fast run of multiple simulations, the building simulation software TRNSYS was coupled with the general optimization software GenOpt® [5], which allows to set parameters and constraints to perform the parametric study. In this way, the energy needs objective function can be calculated by TRNSYS using as input the parameter values selected by GenOpt. The process is shown in Fig.3: the parametric algorithm of GenOpt varies the value of one parameter at a time from its minimum to its maximum value with a discrete variation step, while the others are fixed to their initial value. The all set of parameter values is entered to TRNSYS, which performs the simulation and calculates the value of the objective function depending on that parameter set. Each simulation with related parameters values are registered by GenOpt in a text file, readable by the user at the end of the run. Values are then ordered and elaborated as spreadsheets by the user.

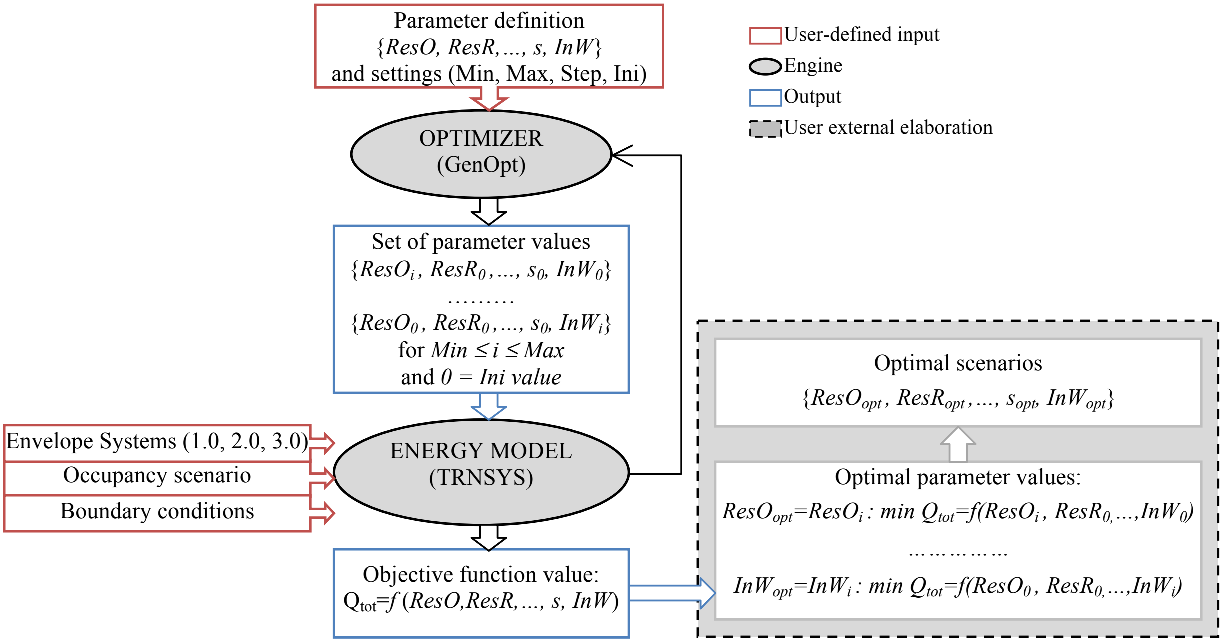

Fig. 3. The input-engine-output process for the parametric study, and the external elaboration for optimization

2.3.1. Parameters

Parameters were defined to identify geometry features or construction features of the building envelope that are able to influence the final energy need of the building. These are referred to the insulation thickness, the window type and dimensions, the solar protection dimension and the amount of internal mass, as represented in Fig.4 and reported in details in Table 1. The range and the step of their variation were set according to regulation requirements (e.g. the minimum window area is set to the limit imposed by the French national regulation), technical feasibility (e.g. the maximum insulation thickness is set to the current technical practice) and market criteria (e.g. the window types are selected among those available on the French market). Features of the selected window types are described in Table 2.

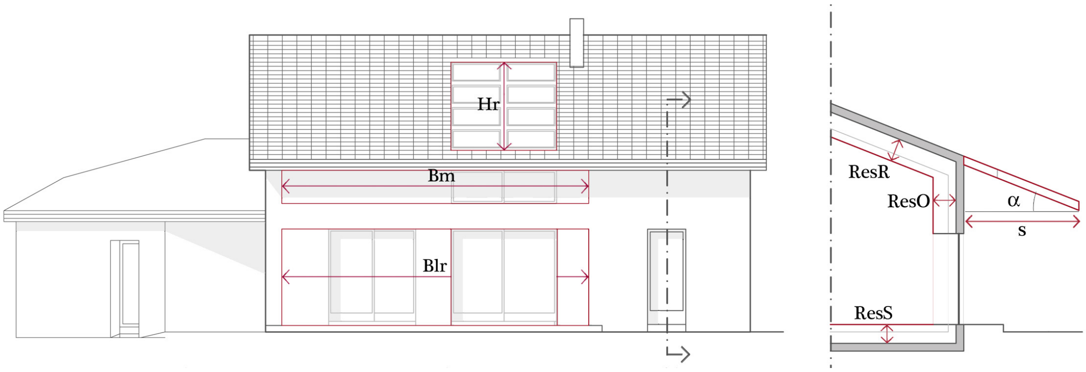

Fig. 4. Parameters: representation on the south front and section

Table 1. Parameters: definition, variability range and step and initial scenarios

Parameter name and description		Unit	Min	Max	Step	INI 1.0.1	INI 1.0.2	INI 1.0ref	INI 1.0.3
ResO	Thermal resistance of wall insulation layer	[m^{2}Kh/kJ]	0.25	5.00	0.25	0.50	1.00	1.75	3.50
ResR	Thermal resistance of roof insulation layer	[m^{2}Kh/kJ]	0.25	5.00	0.25	0.75	2.00	3.50	4.50
ResS	Thermal resistance of slab insulation layer	[m^{2}Kh/kJ]	0.25	3.00	0.25	0.50	1.50	2.50	3.00
WT	Window Type of North - East -West walls	[-]	1	5	1	1	2	4	5
WTS	Window Type of South wall	[-]	1	5	1	1	2	4	5
WTR	Window Type of Roof	[-]	1	5	1	1	2	4	5
Blr	Ground floor south window width (h= 2.15 m)	[m]	2.20	7.80	0.20	4.20	4.20	4.20	4.20
Bm	First floor south window width (h= 0.80 m)	[m]	0.20	7.80	0.20	2.40	2.40	2.40	2.40
Hr	Roof window height (w= 2.28 m)	[m]	0.00	4.72	0.59	4.72	4.72	4.72	4.72
s	Roof south overhang width	[m]	0.20	3.60	0.20	0.90	0.90	0.90	0.90
InW	Thickness of layers of inertial wall	[m]	0.02	0.20	0.02	0.20	0.20	0.20	0.20

Table 2. Window type description

Type	Description		U-value [W/(m^{2}K)]	g-value
1	4/16/4	Double glazing	2.00	0.70
2	3/12.7/2.5	Double glazing, low emissivity	1.76	0.59
3	4/16/4	Double glazing, low emissivity with Argon	1.43	0.58
4	4/16/4/16/4	Triple glazing	0.70	0.50
5	4/16/4/16/4	Triple glazing, with Argon	0.40	0.40

As all design variables in a building are interrelated, the impact of the variation of one parameter on the final energy demand depends on values of other parameters. That is why the parametric study was performed using different sets of initial values, the Initial Scenarios (INIs).

First, the INI related to the actual configuration of the CSB was considered. It is called “1.0 ref”: the first number identifies the envelope system type (1=Blocks with internal insulation – the actual envelope of CSB), the second number equal to 0 indicates that no energy system is taken in account and “ref” means that it represents the reference case-study configuration. Then, three more INIs were set: the so-called “1.0.1” scenario corresponds to a low-performance building, the “1.0.2” scenario represents a medium-performance building and scenario“1.0.3” is related to a very-high-performances building. The “1.0 ref” is considered a high-performance scenario, situated between the medium scenario and the very high scenario. Parameter values of the INIs are shown in Table 1.

2.3.2. Envelope systems

In order to evaluate not only the effect of changing the construction layer thickness, but also the effect of varying the layer order and the materials of opaque envelope, two more envelope systems were modeled in addition to that referred to the actual CSB. The Envelope System (ES) 2.0 was created inverting the wall layer order of ES 1.0: the insulation was put on the external side, creating an Exterior Insulation and Finishing System (EIFS). The aim was to evaluate the variation in energy needs as a function of the internal inertial mass. Roof and slab are the same of ES 1.0. The ES 3.0 uses the Oriented Strand Board system for external walls and roof: the insulated wooden panel layer is completed with an additional EIFS package. The aim is to evaluate the difference between a massive (like ES 1.0 or ES 2.0) and a light envelope. The slab of ES 3.0 is equal to the previous ones.

Four INIs were set also for ES 2.0 and ES 3.0. Both INI 2.0ref and 3.0ref were created with geometric criteria, having the total thickness of envelope surfaces equal to that of the INI 1.0ref. As the plan and the geometry of the building do not change, the parametric studies of these ESs were carried out taking into account the same parameters presented in section 2.3.1. The only differences in settings of the parameters are reported in Table 3 and 4. They are due to technical feasibility and modelling limits of the EIFS package. The ResO parameter for CSB 3.0 refers only to the additional external insulation.

Table 3. Different settings for parameters of ES 2.0

Parameter	Unit	Min	Max	Step	INI 2.0.1	INI 2.0.2	INI 2.0ref	INI 2.0.3
ResO	[m^2Kh/kJ]	0.25	2.25	0.25	0.50	1.00	1.75	2.25

Table 4. Different settings for parameters of ES 3.0

Parameter	Unit	Min	Max	Step	INI 3.0.1	INI 3.0.2	INI 3.0ref	INI 3.0.3
ResO	[m^2Kh/kJ]	0.25	2.25	0.25	0.50	1.00	1.75	2.25
ResR	[m^2Kh/kJ]	0.25	3.00	0.25	0.75	1.50	2.25	3.00

2.3.3. Objective function

As already mentioned, the objective function is represented by the total annual energy need of the CSB. As TRNSYS calculates separately heating and cooling needs, they were added together in terms of primary energy using the equation (1), where heating energy is weighted with a primary energy factor of 1 (gas boiler), and cooling energy is reported into electricity considering an Energy Efficiency Ratio (EER) equal to 3 and then weighted with a primary energy factor of 2.58 (standard French regulations).

$$Q_{total} = Q_{heating} + \frac{Q_{cooling}}{3} \cdot 2.58 \tag{1}$$

2.3.4. Optimization process

For each INI of each ES, the process shown in Fig. 3 was used to identify the optimal value of each parameter (e.g. *$ResO_{opt}$*), that is the value that minimizes the objective function. For each ES, four optimal scenarios (OPTs) were identified starting from its four INIs. The three best OPTs, each related to one ES, were compared and evaluated, in order to identify the OPT leading to the minimum energy needs.

3. Results

Results are presented into graphs that have on the vertical axis the percentage value indicating the variation in energy performance for heating, cooling and total (the objective function) related to the variation of the variable on the horizontal axis (be it: the range of variability of one parameter, a set of INIs or OPTs). Each graph has a reference value, which is the value that the quantity assumes in the INI simulation: the percentage equal to zero corresponds to the reference x-value, and positive values of percentage correspond to the increase of energy performance (savings in energy needs with respect to the reference value), while negative values represent the decrease of energy performance. Moreover, some histograms report on the vertical axis the values of energy needs in kWh/m^2/year of primary energy.

3.1. Initial scenarios

The relationship between the energy performances of the INIs of ES 1.0 is presented on Fig. 5a: the three INIs are evaluated with respect to the reference (1.0ref). The comparisons between INIs of the three ESs are reported in the histogram of Fig.5b, where the total annual energy need is split in heating and cooling needs.

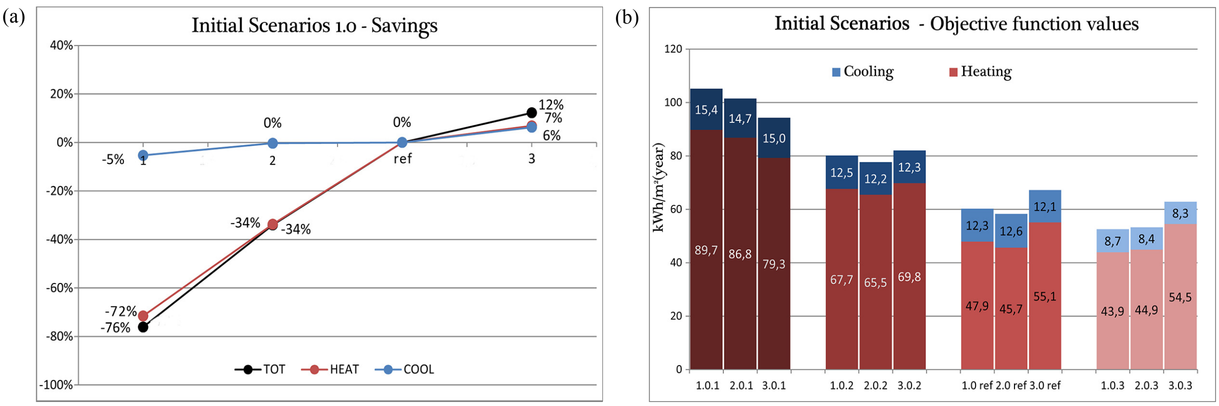

Fig.5. Initial scenarios. (a)Percentage of savings of Ini scenarios of ES 1.0. (b) Energy performance comparison of all INIs.

3.2. Parameters

Here are presented some results related to the variation of some parameters. In each diagrams, the “INI” value of parameter is recognizable in the point where the curve intersects the horizontal axis. The highest point of the curve corresponds to the optimal value of the parameter.

The diagram in Fig.6a shows the impact of the variation of parameter ResO on cooling, heating and total need (the objective function of equation (1)) of INI 1.0ref: a higher insulation of external walls corresponds to a lower heating need, while the cooling need increases. The diagram in Fig.6b shows the variation of total needs of INI 1.0ref as a function of the variation of ResO, ResR and ResS parameters: in all cases, the higher insulation, the higher energy savings are. Variation curves of heating and cooling needs are reported in diagrams of Fig 6c and 6d, in both summer and winter cases. In case of outwall and ground slab an increase of insulation corresponds to an increase of heating savings and a decrease of cooling savings, while in roof case the insulation increase causes energy savings during all the year. This is due to the fact that most of the roof surface is south oriented and has high solar absorption: if not well insulated, the heat transfer through the roof surface causes the overheating of the indoor environment.

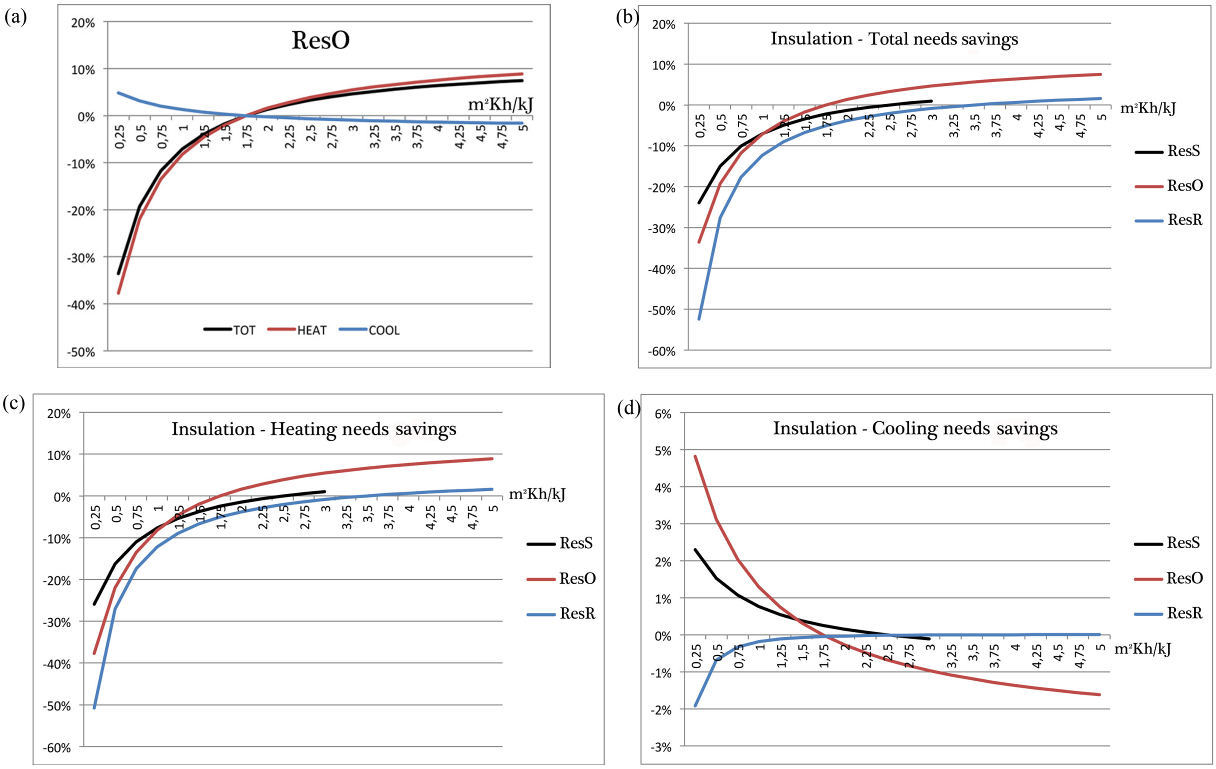

Fig.6. Insulation parameters. (a)Variation of cooling, heating and total needs of INI 1.0ref related to parameter ResO. (b) (c) (d) Comparison between savings produced by variation of parameters ResO, ResS, ResR on total, heating and cooling needs.

The variation curves of energy needs of INI 1.0 ref, related to the variation of parameter Hr, are shown in Fig. 7a, similarly to those of Fig. 6a. The Fig. 6b reports the curves related to total needs of the four INIs of ES 1.0, indicating a different optimal value of the parameter Hr for each INI. In all cases, the highest energy savings are produced by a reduction of the roof window dimension. This is good also for thermal comfort, as a large window on a heavily insulated structure may cause overheating and high indoor temperature stratification, due to the entering large amount of direct solar radiation.

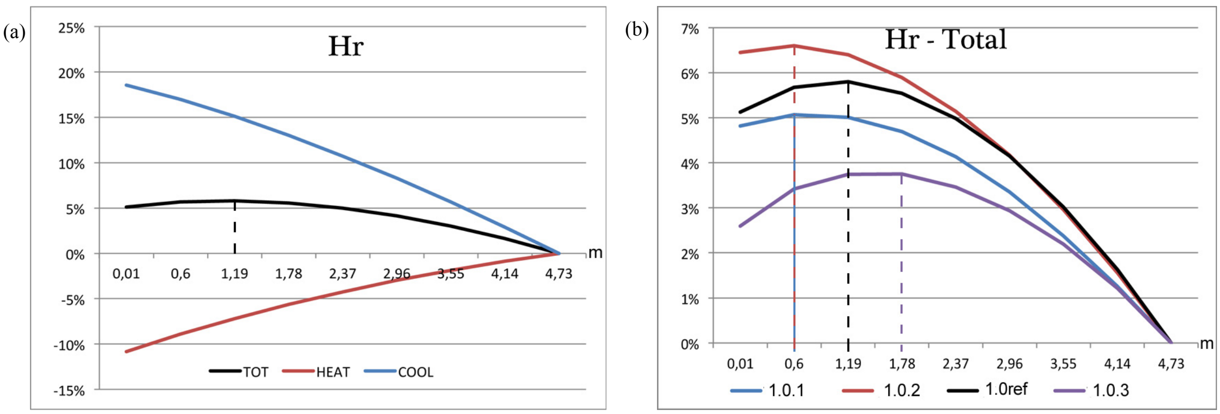

Fig.7. Parameter Hr. (a)Variation of heating, cooling and total needs of INI 1.0ref. (b) Variation of total needs of all INIs of ES 1.0.

3.3. Optimal scenarios

As explained in section 2.3.4, the parametric studies led to one OPT for each defined INI. All the optimal values of parameters of the OPTs are reported in Table 5, together with the initial configuration of CSB (INI 1.0ref). It is shown that the optimal value of some parameters, such as those concerning insulation or window type, corresponds to the maximum value of the range of each parameter (reported in Table 1). For other parameters, such as Hr and s, the optimal value strictly depends on other variables, since the optimal value varies depending on INI. The last row reports the objective function values of each scenario: for each ES, the OPT leading to the minimum objective function value is colored in grey.

Table 5. Optimal scenarios

Par.	Unit	INI 1.0ref	OPT 1.0.1	OPT 1.0.2	OPT 1.0ref	OPT 1.0.3	OPT 2.0.1	OPT 2.0.2	OPT 2.0ref	OPT 2.0.3	OPT 3.0.1	OPT 3.0.2	OPT 3.0ref	OPT 3.0.3
ResO	[m^2Kh/kJ]	1.75	5.00	5.00	5.00	5.00	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
ResR	[m^2Kh/kJ]	3.50	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	3.00	3.00	3.00	3.00
ResS	[m^2Kh/kJ]	2.50	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
WT	[-]	4	5	5	5	5	5	5	5	5	5	5	5	5
WTS	[-]	4	5	5	5	5	5	5	5	5	5	5	5	5
WTR	[-]	4	5	5	5	5	5	5	5	5	5	5	5	5
Blr	[m]	4.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20
Bm	[m]	2.40	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Hr	[m]	4.72	0.60	0.60	1.18	0.90	1.18	0.60	1.18	1.77	0.60	0.60	1.18	1.77
s	[m]	0.90	0.20	0.20	0.90	0.20	0.20	0.20	1.30	0.20	0.40	0.20	0.80	0.20
InW	[m]	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Objective function [kWh_{ep}/m^2/year]		58.50	46.82	46.60	46.82	48.10	49.01	49.45	49.17	49.45	59.35	59.32	59.01	58.77

The Fig.8a shows the percentage of energy saving produced by each OPTs defined in Table 5 with respect to the actual CSB configuration (INI 1.0ref). The Fig.8b compares the energy needs of the grey OPTs with those of INI 1.0ref. As shown, the OPT 1.0.2 resulted in the best performance.

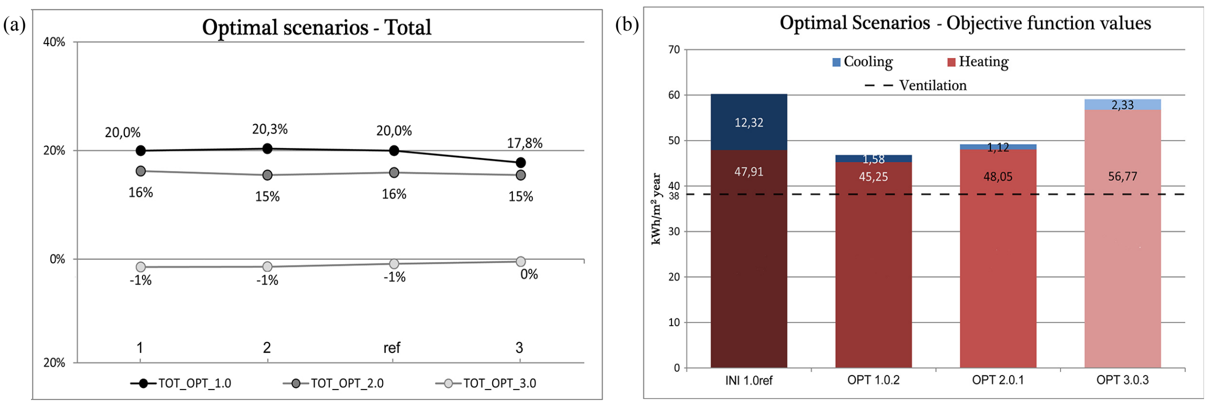

Fig.8 (a) Savings produced by OPTs with respect to INI 1.0ref. (b) Objective function values of the grey OPTs of Table 5.

The dotted black line in fig.8b indicates the heating energy need due to the natural ventilation, which was estimated to be around 38 $kWh_{ep}/m^2/year$ for the ventilation rate of 0.7 ach. Considering a mechanical double-flux ventilation system with heat recovery (70% efficiency), the energy needs would be strongly reduced, as reported in Table 6. If these performances were combined with a high performance system and the exploitation of renewable energy sources, the optimized building would easily become a nZEB.

Table 6. Total annual energy needs with the mechanical ventilation system and savings with respect to INI 1.0 ref

Parameter Unit	INI 1.0 ref	OPT 1.0.2	OPT 2.0.1	OPT 3.0.3
Total annual energy needs [$kWh_{ep}/m^2/year$]	31.1	20.0	22.4	31.4
Savings	-	36%	28%	-1%

4. Conclusions

This study allows some widely applied principles for designing nZEB, such as a high-insulated envelope and the importance of designing geometry and construction of windows and shading elements to be verified. Furthermore, since the design of a nZEB has always to deal with the trade-off between heating and cooling needs reduction, as some energy efficiency measures reduce the heating needs while increase the cooling needs, or viceversa, it is necessary to use parametric analysis tools able to assess this trade-off between different parameters on heating and cooling needs in an integrated fashion [6]. In conclusion, this study demonstrates that the technical optimum of a nZEB is not the product of a simple sum of performances related to the optimal value of each parameter, but it is determined by the optimal interaction between the design parameters. Therefore, the resulted optimal scenario may not reflect the absolute optimal solution, as this study did not evaluate all the combination of parameter values. Further studies are being performed in order to refine the method, exploring other optimization algorithms, and also to include the energy system within the optimization process.

Acknowledgements

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